

# Measurements of Branching Fraction and Polarization in $B^+ \rightarrow \rho^+ K^{*0}$ Decay

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We present the results of a study of the charmless vector-vector decay  $B^+ \rightarrow \rho^+ K^{*0}$ , based on 253  $\text{fb}^{-1}$  of data collected with the Belle detector at the KEKB asymmetric-energy  $e^+e^-$  collider. We obtain the branching fraction  $\mathcal{B}(B^+ \rightarrow \rho^+ K^{*0}) = (8.9 \pm 1.7(\text{stat}) \pm 1.2(\text{syst})) \times 10^{-6}$ . We also perform a helicity analysis of the  $\rho$  and  $K^*$  vector mesons, and obtain the longitudinal polarization fraction  $f_L(B^+ \rightarrow \rho^+ K^{*0}) = 0.43 \pm 0.11(\text{stat})^{+0.05}_{-0.02}(\text{syst})$ .

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Naive factorization in the Standard Model (SM) predicts that the longitudinal polarization fraction ( $f_L$ ) in  $B$  meson decays to light vector-vector (VV) final states is close to unity [1]. In the tree dominated  $B^+ \rightarrow \rho^+ \rho^0$  and  $B^0 \rightarrow \rho^+ \rho^-$  decays, this prediction has been confirmed [2, 3, 4]. In contrast, for the pure  $b \rightarrow s$  penguin  $B \rightarrow \phi K^*$  decay, Belle [5] and BaBar [4] have found that the longitudinal and transverse polarization fractions are comparable, which is in disagreement with the factorization expectation. Possible explanations for this discrepancy include enhanced non-factorizable contributions such as penguin annihilation [1], large  $SU(3)$  breaking in form factors [6], or new physics [7, 8]. It is therefore important to perform polarization measurements in other VV modes, in particular, in the pure penguin  $b \rightarrow s d\bar{d}$  decay  $B^+ \rightarrow \rho^+ K^{*0}$ .

In this paper, we present the results of a study of  $B^+ \rightarrow \rho^+ K^{*0}$  decays [9] with a 253  $\text{fb}^{-1}$  data sample containing  $275 \times 10^6$   $B$  meson pairs collected with the Belle detector at the KEKB asymmetric-energy  $e^+e^-$  collider [10] operating at the  $\Upsilon(4S)$  resonance ( $\sqrt{s} = 10.58 \text{ GeV}$ ). The production rates for  $B^+ B^-$  and  $B^0 \bar{B}^0$  pairs are assumed to be equal.

The Belle detector is a large solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect  $K_L^0$  mesons and to identify muons (KLM). The detector is described in detail elsewhere [11].

We select  $B^+ \rightarrow \rho^+ K^{*0}$  candidate events by combining three charged tracks (two oppositely charged pions and one kaon) and one neutral pion. Each charged track is required to have a transverse momentum  $p_T > 0.1 \text{ GeV}/c$  and to have an origin within 0.2 cm in the radial direction and 5 cm along the beam direction of the interaction point (IP).

Particle identification likelihoods for the pion and kaon hypotheses are calculated by combining information from the TOF and ACC systems with  $dE/dx$  measurements in the CDC. To identify kaons, we require the kaon likelihood ratio,  $L_K/(L_K + L_\pi)$ , to be greater than 0.6. To identify pions, we require  $L_K/(L_K + L_\pi)$  to be less than 0.4. The efficiency for this selection is 86% for kaons and 89% for pions, with corresponding  $\pi/K$  misidentification rates of 8% and 10%. In addition, charged tracks are rejected if they are consistent with an electron hypothesis.

Candidate  $\pi^0$  mesons are reconstructed from pairs of photons that have an invariant mass in the range  $0.1178 - 0.1502 \text{ GeV}/c^2$ , corresponding to a window of  $\pm 3\sigma$  around the nominal  $\pi^0$  mass. The photons are assumed to originate from the IP. The energy of each photon in the laboratory frame is required to be greater than 50 MeV for the ECL barrel region ( $32^\circ < \theta < 129^\circ$ ) and 100 MeV for the ECL endcap regions ( $17^\circ < \theta < 32^\circ$  and  $129^\circ < \theta < 150^\circ$ ), where  $\theta$  denotes the polar angle of the photon with respect to the beam line. The  $\pi^0$  candidates are kinematically constrained to the nominal  $\pi^0$  mass. In order to reduce the combinatorial background, we only accept  $\pi^0$  candidates with momenta  $p_{\pi^0} > 0.40 \text{ GeV}/c$  in the  $e^+e^-$  center-of-mass (CM) system.

Candidate  $\rho^+$  mesons are reconstructed via their  $\rho^+ \rightarrow \pi^+ \pi^0$  decay, and the  $\pi^+ \pi^0$  pairs are required to have an invariant mass in the region  $0.62 \text{ GeV}/c^2 <$

$M(\pi^+\pi^0) < 0.92 \text{ GeV}/c^2$ . Candidate  $K^{*0}$  mesons are selected from the  $K^{*0} \rightarrow K^+\pi^-$  decay with an invariant mass  $0.83 \text{ GeV}/c^2 < M(K^+\pi^-) < 0.97 \text{ GeV}/c^2$ .

To isolate the signal, we form the beam-constrained mass  $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$ , and the energy difference  $\Delta E \equiv E_B - E_{\text{beam}}$ , where  $E_{\text{beam}}$  is the CM beam energy, and  $p_B$  and  $E_B$  are the CM momentum and energy, respectively, of the  $B$  candidate. The  $\Delta E$  distribution has a tail on the lower side caused by incomplete longitudinal containment of electromagnetic showers in the CsI(Tl) crystals. We accept events in the region  $M_{bc} > 5.2 \text{ GeV}/c^2$  and  $-0.3 \text{ GeV} < \Delta E < 0.3 \text{ GeV}$ , and define a signal region in  $M_{bc}$  and  $\Delta E$  as  $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$  and  $-0.10 \text{ GeV} < \Delta E < 0.06 \text{ GeV}$  respectively. These requirements correspond to approximately  $\pm 3\sigma$  for both quantities.

The continuum process  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) is the main source of background and must be strongly suppressed. One method of discriminating the signal from continuum is based on the event topology, which tends to be isotropic for  $B\bar{B}$  events and jet-like for  $q\bar{q}$  events. Another discriminating characteristic is  $\theta_B$ , the CM polar angle of the  $B$  flight direction.  $B$  mesons are produced with a  $1 - \cos^2 \theta_B$  distribution while continuum background events tend to be uniform in  $\cos \theta_B$ . The displacement along the beam direction between the signal  $B$  vertex and that of the other  $B$ ,  $\Delta z$ , also provides separation. For  $B$  events, the average value of  $\Delta z$  is approximately  $200 \mu\text{m}$ , while continuum events have a common vertex. Additional discrimination is provided by the  $b$ -flavor tagging algorithm [12] developed for time-dependent analysis at Belle. The flavor tagging procedure yields two outputs:  $q$  ( $= \pm 1$ ), which indicate the flavor of the tagging  $B$ , and  $r$ , which ranges from 0 to 1, is a measure of the likelihood that the  $b$  flavor of the accompanying  $B$  meson is correctly assigned. For signal events,  $q$  is more likely consistent with the opposite of the charge of signal  $B$ ; there is no correlation for continuum events. Events with high values of  $r$  are well-tagged and are less likely to originate from continuum production. Thus, the quantity  $q \cdot r \cdot C_B$ , where  $C_B$  is the charge of the signal  $B$ , can be used to discriminate against continuum events.

We use Monte Carlo (MC) simulated signal and data sideband (defined as  $5.2 \text{ GeV}/c^2 < M_{bc} < 5.26 \text{ GeV}/c^2$ ) events to form a Fisher discriminant based on a set of modified Fox-Wolfram moments [13] that are confirmed to be uncorrelated with  $M_{bc}$ ,  $\Delta E$  and variables considered later in the analysis. Probability density functions (PDFs) derived from the Fisher discriminant, the  $\cos \theta_B$  distributions and the  $\Delta z$  distributions are multiplied to form likelihood functions for signal ( $\mathcal{L}_s$ ) and continuum background ( $\mathcal{L}_{q\bar{q}}$ ); these are combined into a likelihood ratio  $\mathcal{R}_s = \mathcal{L}_s / (\mathcal{L}_s + \mathcal{L}_{q\bar{q}})$ . We achieve background suppression by imposing  $q \cdot r \cdot C_B$ -dependent  $\mathcal{R}_s$  requirements, which are determined by optimizing the figure of merit,

$S/\sqrt{S+B}$ , where  $S$  ( $B$ ) is the number of signal (background) events in the signal region. A branching fraction of  $\mathcal{B}(B^+ \rightarrow \rho^+ K^{*0}) = 1 \times 10^{-5}$  is assumed. This requirement removes 99.3% of the continuum background while retaining 41% of the  $B^+ \rightarrow \rho^+ K^{*0}$  events. The MC-determined efficiency with all selection criteria imposed is 2.7% for longitudinal polarization ( $A_0$ ) and 4.0% for transverse polarization ( $A_\pm$ ).

The fraction of multiple candidates in the signal region for signal MC is 3.6% for the  $A_0$  helicity state and 1.7% for the  $A_\pm$  state. We allow multiple candidates in this analysis.

To investigate backgrounds from  $b \rightarrow c$  decays, we use a sample of  $B\bar{B}$  MC events corresponding to an integrated luminosity of  $412 \text{ fb}^{-1}$ . We find a contribution from  $B^+ \rightarrow \overline{D}^0(K^+\pi^-\pi^0)\pi^+$  decays in the  $\rho$  or  $K^*$  sideband region and require  $|M(K\pi\pi^0) - M_{D^0}| > 0.050 \text{ GeV}/c^2$  to veto these events. This requirement does not remove any  $B^+ \rightarrow \rho^+ K^{*0}$  events. Among the charmless  $B$  decays, potential backgrounds arise from  $B^+ \rightarrow a_1^0 K^+$ ,  $B^+ \rightarrow \rho^+ K_0^*(1430)$ , non-resonant  $B^+ \rightarrow \rho^+ K^+\pi^-$  and  $B^+ \rightarrow K^{*0}\pi^+\pi^0$ . We separate signal from these backgrounds by fitting the  $\rho$  and  $K^*$  invariant mass distributions.

We extract the signal yield by applying an extended unbinned maximum-likelihood fit to the two-dimensional  $M_{bc}$ - $\Delta E$  distribution. The fit includes components for signal plus backgrounds from continuum events and  $b \rightarrow c$  decays. The PDFs for signal and  $b \rightarrow c$  decay are modeled by smoothed two-dimensional histograms obtained from large MC samples. The signal PDF is adjusted to account for small differences observed between data and MC for a high-statistics mode containing  $\pi^0$  mesons,  $B^+ \rightarrow \overline{D}^0(K^+\pi^-\pi^0)\pi^+$ . The continuum PDF is described by a product of a threshold (ARGUS) function [14] for  $M_{bc}$  and a first-order polynomial for  $\Delta E$ , with shape parameters allowed to vary. All normalizations are allowed to float. Figure 1 shows the final event sample and the fit results. The five-parameter (three normalizations plus two shape parameters for continuum) fit yields  $134.8 \pm 16.9$   $B^+ \rightarrow K^+\pi^-\pi^+\pi^0$  events.

We further distinguish the  $\rho^+ K^{*0}$  signal from non-resonant decays such as  $B^+ \rightarrow \rho^+ K^+\pi^-$  or  $B^+ \rightarrow K^{*0}\pi^+\pi^0$  by fitting the  $M(\pi^+\pi^0)$  and  $M(K^+\pi^-)$  invariant mass distributions. The signal yields obtained from the  $M_{bc}$ - $\Delta E$  fit for different  $M(\pi\pi)$  and  $M(K\pi)$  bins are plotted in Fig. 2, where the  $M(\pi\pi)$  distribution is for events in the  $K^*$  region ( $0.83 \text{ GeV}/c^2 < M(K\pi) < 0.97 \text{ GeV}/c^2$ ) and the  $M(K\pi)$  distribution is for events in the  $\rho$  region ( $0.62 \text{ GeV}/c^2 < M(\pi\pi) < 0.92 \text{ GeV}/c^2$ ). We perform separate  $\chi^2$  fits to the  $M(\pi\pi)$  or  $M(K\pi)$  distributions. Each fit includes components for signal and non-resonant background. The signal  $\rho$  and  $K^*$  PDFs are modeled by relativistic  $P$ -wave Breit-Wigner functions with means and widths fixed at their known values [15]; the PDFs are convolved with a Gaussian of

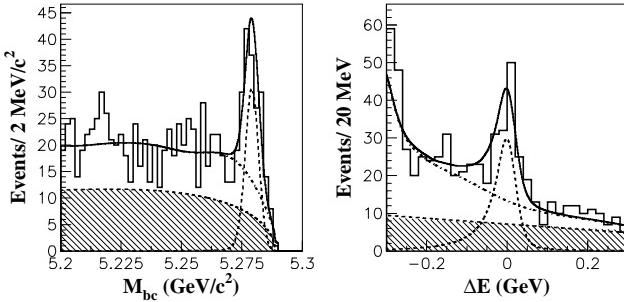


FIG. 1: Projections of  $M_{bc}$  for events in the  $\Delta E$  signal region (left), and projection of  $\Delta E$  in the  $M_{bc}$  signal region (right). The solid curves show the results of the fit. The hatched histograms represent the continuum background. The sum of the  $b \rightarrow c$  and continuum background component is shown as dot-dashed lines.

$\sigma = 5.3$  MeV, which is obtained by fitting the  $D^0(K^-\pi^+)$  invariant mass, to account for the detector resolution. The non-resonant component is represented by a threshold function with parameters determined from MC events where the final states are distributed uniformly over phase space. The  $M(\pi\pi)$  mass fit gives  $125.4 \pm 15.8$   $\rho$  and  $-0.3 \pm 3.0$  non-resonant  $K^{*0}\pi^+\pi^0$  events in the  $\rho$  mass region. In the  $M(K\pi)$  fit, we find  $85.4 \pm 16.1$   $\rho K\pi$  signal and  $28.8 \pm 4.1$  non-resonant events in the  $K^*$  mass region. The statistical significance of the signal, defined as  $\sqrt{\chi_0^2 - \chi_{\min}^2}$ , where  $\chi_{\min}^2$  is the  $\chi^2$  value at the best-fit signal yield and  $\chi_0^2$  is the value with the  $K^{*0}$  signal yield set to zero, is  $5.3\sigma$  ( $5.2\sigma$  with the inclusion of systematics). The contribution from non-resonant  $\rho^+K^+\pi^-$  is significant and is taken into account in both the branching fraction and polarization determinations, while we neglect the non-resonant  $K^{*0}\pi^+\pi^0$  contribution.

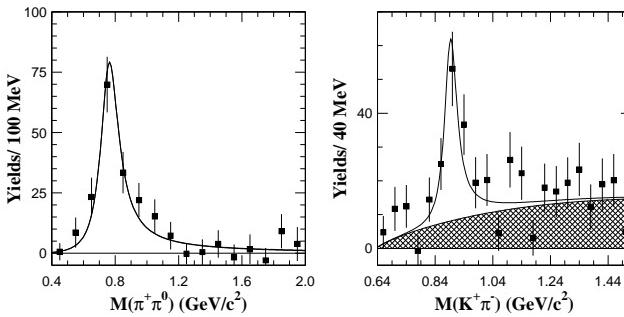


FIG. 2: Signal yields obtained from the  $M_{bc}$ - $\Delta E$  distribution in bins of  $M(\pi^+\pi^0)$  (left) for events in the  $K^{*0}$  region and in bins of  $M(K^+\pi^-)$  (right) for events in the  $\rho$  region. Solid curves show the results of the fit. Hatched histograms are for the non-resonant component.

We use the  $\rho^+ \rightarrow \pi^+\pi^0$  and  $K^{*0} \rightarrow K^+\pi^-$  helicity-angle ( $\theta_\rho$ ,  $\theta_{K^*}$ ) distributions to determine the relative

strengths of  $|A_0|^2$  and  $|A_\pm|^2$ . Here  $\theta_\rho$  ( $\theta_{K^*}$ ) is the angle between an axis anti-parallel to the  $B$  flight direction and the  $\pi^+$  ( $K^+$ ) flight direction in the  $\rho$  ( $K^*$ ) rest frame. For the longitudinal polarization case, the distribution is proportional to  $\cos^2 \theta_\rho \cos^2 \theta_{K^*}$ , and for the transverse polarization case, it is proportional to  $\sin^2 \theta_\rho \sin^2 \theta_{K^*}$  [16]. Figure 3 shows the signal yields obtained from  $M_{bc}$ - $\Delta E$  fits in bins of the cosine of the helicity angle for  $\rho$  and  $K^*$ . We perform a binned simultaneous  $\chi^2$  fit to the  $\rho$  and  $K^*$  helicity-angle distributions. The fit includes components for signal and non-resonant  $\rho K\pi$ . PDFs for signal  $A_0$  and  $A_\pm$  helicity states are determined from the MC simulation. The helicity-angle distribution for data in the high  $M(K\pi)$  sideband region  $1.1 \text{ GeV}/c^2 < M(K\pi) < 1.5 \text{ GeV}/c^2$ , where  $\rho K\pi$  events dominate, is consistent with a  $\cos^2 \theta$ -like  $\cos \theta_\rho$  and a flat  $\cos \theta_{K^*}$  distribution. Thus, we assume an  $S$ -wave  $K\pi$  system and model the non-resonant  $B \rightarrow \rho K\pi$  PDF based on the MC simulation. The fraction of the non-resonant component is fixed at the values obtained from the  $K^*$  mass fit. The two-parameter (normalizations for  $A_0$  and  $A_\pm$ ) fit result deviates from 100% longitudinal polarization with a significance of  $4.9\sigma$  ( $4.3\sigma$  including systematic uncertainties). The significance is defined as  $\sqrt{\chi_0^2 - \chi_{\min}^2}$ , where  $\chi_{\min}^2$  is the  $\chi^2$  value at the best-fit and  $\chi_0^2$  is the value with the longitudinal polarization fraction set to 100%.

The largest uncertainties in the polarization measurement are due to uncertainties in the non-resonant  $\rho K\pi$  PDF, potential scalar-pseudoscalar ( $S$ - $P$ ) interference, and the non-resonant fraction. We assign a  $+10.3\%$  systematic error for the non-resonant PDF. This uncertainty is estimated by adding a 1/3 flat component to the  $\rho$  helicity PDF for non-resonant  $\rho K\pi$  in the helicity fit. Interference of the longitudinal amplitude  $A_0$  with the  $S$ -wave ( $K\pi$ ) system introduces a term with a  $2e^{i\Delta\phi}|A_{\rho K\pi}|\cos \theta_{K^*}$  dependence, where  $\Delta\phi$  is the phase difference and  $|A_{\rho K\pi}|$  is the amplitude of the  $B \rightarrow \rho K\pi$  decay. The  $S$ - $P$  wave interference disappears in the  $\cos \theta_\rho$  distribution, which is integrated over  $\cos \theta_{K^*}$ ; however it remains in the  $\cos \theta_{K^*}$  distribution. We include an additional linear function for the interference term in the  $\cos \theta_{K^*}$  helicity, and redo the  $\chi^2$  fit. The resulting small change in  $f_L$ , 0.5%, is assigned as the systematic uncertainty for the  $S$ - $P$  interference. A  $+4.0\%$ / $-4.1\%$  systematic error is assigned for the uncertainty in the fraction of non-resonant  $\rho K\pi$ , obtained by varying the non-resonant fraction by  $\pm 1\sigma$ . Adding the various systematic error contributions in quadrature, we obtain the longitudinal polarization fraction in  $B^+ \rightarrow \rho^+ K^{*0}$  decays

$$f_L(B^+ \rightarrow \rho^+ K^{*0}) = 0.43 \pm 0.11(\text{stat})^{+0.05}_{-0.02}(\text{syst}).$$

To calculate the  $B^+ \rightarrow \rho^+ K^{*0}$  branching fraction, we use the  $M(K\pi)$  invariant mass fit result and MC-determined efficiencies weighted by the measured polarization components. We consider systematic errors in the

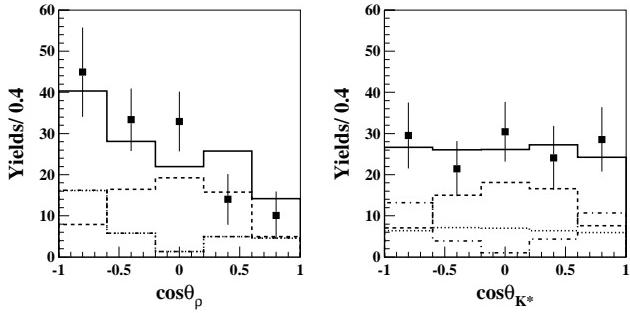


FIG. 3: Fit to background-subtracted helicity distributions. The solid histograms show the results. The dot-dashed (dashed) histograms are the  $A_0$  ( $A_{\pm}$ ) component of the fit; the dotted histograms are for non-resonant  $\rho K \pi$ . The low event yield near  $\cos \theta_\rho = 1$  is due to the  $p_{\pi^0} > 0.4 \text{ GeV}/c$  requirement.

branching fraction that are caused by uncertainties in the efficiencies of track finding, particle identification,  $\pi^0$  reconstruction, continuum suppression, fitting, polarization fraction. We assign an error of 1.1% per track for the uncertainty in the tracking efficiency. This uncertainty is obtained from a study of partially reconstructed  $D^*$  decays. We also assign an uncertainty of 0.7% per track on the particle identification efficiency, based on a study of kinematically selected  $D^{*+} \rightarrow D^0 \pi^+$ ,  $D^0 \rightarrow K^- \pi^+$  decay. A 4.0% systematic error for the uncertainty in the  $\pi^0$  detection efficiency is determined from data-MC comparisons of  $\eta \rightarrow \pi^0 \pi^0 \pi^0$  with  $\eta \rightarrow \pi^+ \pi^- \pi^0$  and  $\eta \rightarrow \gamma \gamma$ . A 4.5% systematic error for continuum suppression is estimated from studying the process  $B^+ \rightarrow \overline{D}^0 \pi^+$ ,  $\overline{D}^0 \rightarrow K^+ \pi^- \pi^0$ . A  $-2.0\% / +1.7\%$  systematic error associated with fits is obtained by shifting each parameter by  $\pm 1\sigma$ . A 6.7% systematic error for the uncertainty in the  $b \rightarrow c$  background PDF is obtained by changing the PDF parameterization. A  $-4.2\% / +4.4\%$  error due to the uncertainty in the fraction of longitudinal polarization is obtained by varying  $f_L$  by its errors. The uncertainty in non-resonant  $K^* \pi \pi$  background gives a contribution of  $-2.2\% / +0\%$  in addition to  $-3.0\% / +2.3\%$  error from uncertainties in the background from other rare  $B$  decays. A 7.1% error for possible bias in the  $\chi^2$  fit [17] is obtained from a MC study. A 1.1% error for the uncertainty in the number of  $B\overline{B}$  events in the data sample is also included. The quadratic sum of all of these errors is taken as the total systematic error. We obtain the branching fraction

$$\mathcal{B}(B^+ \rightarrow \rho^+ K^{*0}) = (8.9 \pm 1.7(\text{stat}) \pm 1.2(\text{syst})) \times 10^{-6}.$$

In summary, we have observed the  $B^+ \rightarrow \rho^+ K^*$  decay with a statistical significance of  $5.3\sigma$ .

We measure the branching fraction to be  $(8.9 \pm 1.7(\text{stat}) \pm 1.2(\text{syst})) \times 10^{-6}$ . We also perform a helicity analysis and find a substantial transversely polarized fraction with a statistical significance of  $4.9\sigma$ . The longitudinal polarization fraction  $f_L$  measured is similar to the surprisingly low value found in  $b \rightarrow sss$  decays  $B \rightarrow \phi K^*$ .

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